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On the Demand for a State-Contingent, Cost-Saving Seed Trait

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Abstract

Biotechnology has enriched the strategy set available to crop managers. Suppose a manager faces a decision between applying a pre-emergence pesticide or applying nothing at all. The advent of pesticide tolerance traits in plants admits the possibility of a state-contingent post-emergence application of pesticide. The innovation adds value in large part because it provides the manager with the option to wait for more information. For heterogeneous acre types, the determinants of trait royalties and of crop management strategies in equilibrium are studied. Pest resistance traits have different implications for crop management. Whereas a tolerance trait likely complements information technologies, the addition of a resistance trait may substitute for them.

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Introduction

Agriculture in North and South America has seen rapid adoption of genetically engineered crop varieties. While demand-side concerns remain as serious impediments to the development of markets for these varieties, cost, yield, and risk considerations have provided the supply side with strong incentives to adopt them (Kalaitzandonakes 1999). This paper is concerned with developing an economic framework to study the advent of a patented state-contingent, cost-saving genetic trait for crops vulnerable to a pest hazard that requires a costly remedy.

The class of hazards in question includes a potentially serious weed problem, where a herbicide tolerance (HT) trait would provide a cheap *ex post* solution to the realized hazard. In 2000, Hess and Duke wrote:

> To date, herbicides that are used in HT crops are applied post-emergence, which allows herbicide application based on need. Unless the weed population is extreme, the application can be delayed until an assessment of the weed population and species present can be made to determine the optimum herbicide type and concentration to use.

It is clear then that HT and other pesticide tolerant (PT) crop varieties provide the flexibility to wait for and use additional relevant information about a pest if and when it becomes available after crop emergence. The class of hazards in question also includes the possibility of an insect infestation, where a pest resistance (PR) trait would obviate the need for *ex post* treatment. Here, too, information and flexibility are important, but, as we will clarify, the manner in which they enter the economics of the PR trait context may differ significantly from that of the PT trait context.

PT- and PR-endowed crop varieties have been major factors in reshaping U.S. agri-input markets from 1996 through 2002 (Fulton and Giannakas 2002; Holmberg 2002;

Fernandez-Corneja, Klotz-Ingram, and Jans 2002). And more of the same may be on the way for the early years of the twenty-first century. Bridges (2000) documented that the U.S. Department of Agriculture (USDA) had processed some 1,584 permits and notices for HT in regulated organisms in 1999, accounting for 27 percent of all such permits and notices.[1] While not all PT varieties have been genetically engineered, genetic engineering was involved in the development of such HT varieties as bromoxynil tolerant cotton (brought to market in 1995), glufosinate tolerant canola and corn (1997), and glyphosate tolerant soybean, canola, cotton, and corn (1996–98). As for PR traits, Bridges identified 2,646 permits and notices on such organisms, the large majority being for insect and virus resistance.[2] While commercialized Bt corn, cotton, and potatoes are the best known instances of PR varieties, potato varieties resistant to the potato leaf roll virus are also on the commercial market.[3]

Although growers quickly may see the merits of a trait, there is no reason to suppose that adoption should be complete, even if trait-endowed varieties receive the same price as conventional varieties (Fulton and Keyowski 1999). Because of location, past cropping practices, or other reasons, acres vary in their susceptibility to any given hazard (Carlson, Marra, and Hubbell 1997). Also, the differences in growers' attitudes toward risks affect the private value of a trait (Hurley, Mitchell, and Rice 2002). Therefore, the optimal strategy for one acre may not be optimal for another.

While the advent of a genetically modified variety may simplify the managerial decision process, it does so by enriching the strategy space available to the manager. A newly available strategy may involve low managerial time requirements (e.g., the need to crop scout may no longer arise), but the manager must choose to adopt that strategy in the first place. Consider the case of a PT trait. Before the commercialization of the tolerance-endowed variety, the manager may have had to decide between (A) incurring a prevention cost to better insure against the hazard, or (B) saving on the prevention cost but taking a yield risk. When the PT variety is available, the strategy space becomes (A) as described, using conventional seed, or (B) as described, using conventional seed, or (C) pay a premium for the trait so that post-emergence remediation of the pest hazard becomes feasible. Our paper inquires into the consequences of enriching the strategy space in this manner.

The problem we seek to shed light on is important for at least two reasons. First, it illustrates a mechanism through which biotechnology and information technology interact in the ongoing disturbances to the structure of agriculture in the Americas. The biotechnology aspect of the problem is clear, whereas the information technology aspect may be less readily apparent. However, upon reflection on strategy C, it should be apparent that the contribution of strategy C to value is predicated upon the revelation of additional information over the intervening time period.[4] Thus in our context, and as will be made clearer in the paper, biotechnology can be an enabling technology that places a premium on a good information structure. We will show that, depending upon the character of the trait, biotechnologies and information technologies can complement or substitute. If the nature of the interactions is predominantly complementary, then it would not be surprising if both of these classes of technology inputs emerged as relevant inputs in crop agriculture at approximately the same time.

Second, and not unrelated to the first, the addition of strategy C has non-trivial implications both for the intensity of agri-chemical use and for the intensity of soil cultivation. As agri-chemicals and intense cultivation tend to generate negative social externalities, a comprehensive study of the enriched strategy space should be illuminating for environmental policy formation.

One of the traditional claims for integrated pest management (IPM) and organic farming practices is that a deeper understanding of one's farm permits more considered husbandry practices. A cost-saving genetic trait may be a technical substitute or complement for a developed data bank of knowledge about the land one manages. A PT trait is a substitute if it eliminates the need for such information. This would be true for information that allows an early judgment on the likely hazard because the PT trait permits the postponement of the application decision. But the PT trait also complements a developed data bank of knowledge about the post-emergence pest status of the crop. However, because PT traits are relatively novel, growers will have had little incentive to develop a data base on assessing pest hazards after the crop has emerged. Thus, PT traits, and through similar reasoning also PR traits, may alter the composition of data sets that growers have incentives to develop. But, regardless of the nature of a grower's extant data set, it does not

necessarily follow that the more informed farmer would be more parsimonious with inputs. Neither does it necessarily follow that a PT trait will reduce the levels of pesticide applications. And the impact may change over time as the grower develops more of the sorts of data bases that are privately optimal in the new environment.

The class of problems we will address fits most clearly into the real options framework. A basic tenet underpinning this literature is that information has value to the extent that it can change actions. In our stylized problem, biotechnology provides the grower with a costly option to defer an action until more information becomes available. A PT trait has the characteristics of a commodity call option in the sense that the biotechnology provides the opportunity to place a floor on crop value in the event of a pest infestation. This option may be availed of by paying the (strike) price of a post-emergence pesticide application. There exists a large literature on valuing such an option and on its implications for actions on the part of the firm (Arrow and Fisher 1974; McDonald and Siegel 1986; Trigeorgis 1998), and we too will study how option values affect decisions. We also will inquire into the implications of grower-level contributors to option value on patent royalties.

Related problems have been analyzed in the agricultural production economics literature. Feinerman, Choi, and Johnson (1990) studied split nitrogen strategies where early application was easy but relatively inefficient at the margin, while late application possibly was not feasible because of weather conditions. In this environment, there is a negative option to wait and apply a late dressing. *Ex ante*, the risk that weather will turn out wet is traded off against the expectation over the gain if nitrogen can be used more effectively. In that work, however, there is no innovative technology that enriches the strategy space.

Site-specific agriculture techniques provide the flexibility necessary for real options to exist. These techniques enrich grower strategy spaces and complement information technologies in the form of global positioning satellites, mapping systems, and nutrient tests (Fee 2002). Babcock and Pautch (1998), to name just one work, have investigated the application and profit implications of this technology complex. For corn in Iowa, they concluded that the option to condition application rates on geographic information increased mean yields and reduced mean application rates.[5]

Our inquiry proceeds with a formalization of a basic two-period environment for pesticide application when acres are heterogeneous and a post-emergence application of the input is precluded. After analyzing this decision-making environment, the PT technology is introduced and we inquire into the determinants of equilibrium royalties and equilibrium varietal plantings. This is followed by a consideration of how heterogeneity in types might affect trait value. We then briefly modify our model to accommodate PR traits. The paper concludes with a deliberation on some additional issues that might warrant formal analysis. In particular, we emphasize the effects of trait innovations on the local demand for farm management expertise.

Basic Model for the Pesticide Tolerant Trait

The model has three time points where the earliest, time point 0, occurs at planting. Time point 1 occurs just after crop emergence, and it may be possible to take an action at this time. Time point 2 is at harvest, when crop value is realized. Crop value depends on pest damage, where pest hazards are random at time point 0 but are non-random at time point 1. As always, the approach taken is to work backwards to solve the problem so that the state-contingent optimal strategies are built into the decision problem that the grower tries to solve.

Acreage susceptibility to pest damage is determined by a large number of factors including cropping history, weather conditions, the use of neighboring land, and past husbandry practices. We capture this heterogeneity in cropland acres through the continuously distributed infestation severity index, θ. The parameter has a continuous cumulative mass distribution $H(\theta)$: $[\theta_l, \theta_u] \rightarrow [0, 1]$ with $H(\theta_u) \equiv 1$. Mass density is $h(\theta)$, and we hold that $H^1(\theta_u) \equiv 1$ for any mass distribution $H^1(\theta)$:$[\theta_l, \theta_u] \rightarrow [0,1]$ that might replace $H(\theta)$ in our analysis so that cropping area is held to be fixed. A grower of acre type θ knows the type at time point 0.

The pest-free crop has value V_{ni} at time point 2 where the subscript may be taken to abbreviate "no infestation." This value is gross of the costs of buying and applying the pesticide, but the cost of standard variety seed has been removed. The seed market is

assumed to be competitive. If infested, the acre has time point 2 value V_i to the grower where $V_i \leq V_{ni}$. This value is random, when viewed from time point 0, with a type-conditioned distribution $G(V_i \mid \theta)$ that has a strictly positive support on $[0,V_{ni}]$. We hold that all growers know the distributions $G(V_i \mid \theta)$ that are pertinent to them at time point 0, so that there does not exist heterogeneity in grower information sets on land husbanded.

It is also held that $G_\theta(V_i \mid \theta) \geq 0 \,\forall\, V_i \in [0,V_{ni}], \forall\, \theta \in [\theta_l, \theta_u]$ in order to model the increasing severity of infestation. Here, the subscripted θ indicates a differentiation. The derivative attribute asserts that conditional distributions are ordered by first-degree stochastic dominance. As a special example, the θ-conditioned expectation of crop value, $E\{V_i \mid \theta\} = \int_0^{V_{ni}} V_i \, dG(V_i \mid \theta)$ is (weakly) decreasing in θ. This may be written as

$$E_\theta\{V_i \mid \theta\} \leq 0 \,\forall\, \theta \in [\theta_l, \theta_u].$$

The acre can be sprayed with pesticide at cost per acre $r = s + F$. Here $r < V_{ni}$ is the total cost per acre of spraying the crop, $s > 0$ is the market cost per acre of the chemical, and $F = 0$ is the fixed per acre cost of spraying. The broad-spectrum pesticide kills all pests and is toxic to the crop so that, absent the PT trait, it cannot be applied after crop emergence. Absent an innovation, the grower has two alternatives at time point 0; (A) to spray at time point 0, or (B) not to spray at all. If strategy A is chosen, the gross crop value is V_{ni} at time point 2 (harvest), while if strategy B is chosen, the gross crop value is realized as V_i.[6]

Absent the Innovation: To Spray or Not to Spray

The per acre value of strategy A to the risk-neutral producer is $U_a(\theta) = V_{ni} - r$, where the expression is invariant to θ. If the grower gambles by refraining from spraying, strategy B, then the expected value of the strategy is $U_b(\theta) = E\{V_i \mid \theta\}$. Since $dU_b(\theta)/d\theta = E_\theta\{V_i \mid \theta\} = 0 = dU_a(\theta)/d\theta$, the acre type so that both strategies deliver the same expected value is given by $\theta_{b,a}$, defined as the solution to

$$V_{ni} - r = E\{V_i \mid q_{b,a}\}. \tag{1}$$

The solution may not be unique because $E\{V_i \mid \theta\}$ is only weakly decreasing in θ. However, the solution set forms a convex set, which we call $\Theta_{b,a}$. As is standard practice, we choose to study the impact of changes on $\hat{\theta}_{b,a} = \sup\{\theta_{b,a} : \theta_{b,a} \in \Theta_{b,a}\}$ (Milgrom and Roberts 1996). In our context, the assumption asserts that indifferent types elect for strategy B. Acre types in $(\hat{\theta}_{b,a}, \theta_u]$ are sprayed before planting, while acre types in $[\theta_l, \theta_{b,a}]$ are not sprayed. It merits observation that threshold type $\theta_{b,a}$ is invariant to mass distribution $H(\theta)$.

Suppose now that the pesticide is off-patent and is produced competitively. With *w* as the constant unit cost of producing the chemical, we have *s* = *w* so that $\bar{H}(\hat{\theta}_{b,a})$ acres are sprayed where $\bar{H}(\theta) = 1 - H(\theta)$ is the type's mass distribution survival function. We have $d\hat{\theta}_{b,a} / dw = -1 / E_\theta\{V_i \mid \theta\} > 0$ from (1) above so that acres under the "don't spray" strategy varies directly with the price of spray, i.e., $dH(\hat{\theta}_{b,a})/dw \geq 0$. We also have that if $H(\theta) \to H^1(\theta)$ where $H(\theta) \geq H^1(\theta) \; \forall \, \theta \in [\theta_l, \theta_u]$ (i.e., first-order dominance in the mass distribution of types), then $\bar{H}(\hat{\theta}_{b,a}) \leq \bar{H}^1(\hat{\theta}_{b,a})$. That is, acreage sprayed increases when the distribution of the infestation index becomes more densely massed towards the upper bound, θ_u. Alternatively, let $G(V_i \mid \theta) \to G^1(V_i \mid \theta)$ such that $G(V_i \mid \theta) \leq G^1(V_i \mid \theta) \; \forall \, \theta \in [\theta_l, \theta_u], \forall \, V_i \in [0, V_{ni}]$ and the probability of a given loss in value rises for each value of θ. Then, from (1), $E\{V_i \mid \theta\}$ declines for each value of θ so that $\hat{\theta}_{b,a} \to \hat{\theta}^1_{b,a} \leq \hat{\theta}_{b,a}$ and $\bar{H}(\hat{\theta}_{b,a}) \leq \bar{H}(\hat{\theta}^1_{b,a})$. Acreage sprayed increases when the expected crop value declines for each acre type.

The Innovation and Grower Actions

Now a technology provider develops and patents the technology underpinning a modified seed that allows the spray to be applied at time point 1, i.e., when it has been established whether a pest problem exists. The grower can now pay a technology fee τ in order to enrich its strategy space to include a third strategy, strategy C. This strategy entails a deferral of the pesticide application decision until after crop emergence so that the information set is larger when the decision is made. Then, in our stylized model, an application of the pesticide on the infested crop will completely restore crop value V_{ni}. We assume that, after waiting, a grower can determine *without noise* what the crop value would be if the opportunity to spray is not taken up. Thus, a pesticide application will occur if and only if $V_{ni} - r > V_i$. The strategy C payoff is $\max[V_{ni} - r, V_i] - \tau$, and the state-contingent payoffs for the three time-0 strategies are provided in Figure 1.

For the grower, the risk-neutral value of the decision to wait for more information is

$$U_c(\theta) = E\{\max[V_{ni} - r, V_i] \mid \theta\} - \tau \qquad (2)$$

with $dU_c(\theta)/d\theta = E_\theta\{\max[V_{ni} - r, V_i] \mid \theta\}$. It is readily shown that $0 = dU_a(\theta)/d\theta \geq dU_c(\theta)/d\theta \geq dU_b(\theta)/d\theta$ so that strategy A is least sensitive to type and strategy B is most sensitive.[7] The intuition behind these inequalities can be found by comparing the strategy payoffs $V_{ni} - r$ for A, $\max[V_{ni} - r, V_i]$ for C, and V_i for B. The strategy A payoff is clearly independent of V_i, and so of θ. Strategy C has limited dependence on V_i, and so on θ, because the grower can remedy the problem *ex post*. The strategy B payoff is not shielded in any way from V_i and so is the most sensitive to θ.

To clarify the effect of the seed trait premium, Figure 1 shows that strategy C is dominant in all states of nature when the trait price is 0 because the trait innovation has provided the grower with a real option of waiting for more information. Then it is clear that $U_c(\theta) \geq \max[U_a(\theta), U_b(\theta)]$ or $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq \max[V_{ni} - r, E\{V_i \mid \theta\}]$ because $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq V_{ni} - r = U_a(\theta)$ and $E\{\max[V_{ni} - r, V_i] \mid \theta\} \geq E\{V_i \mid \theta\}$.[8] In other words, when $\tau = 0$ then the free "option to spray" strategy is preferred over

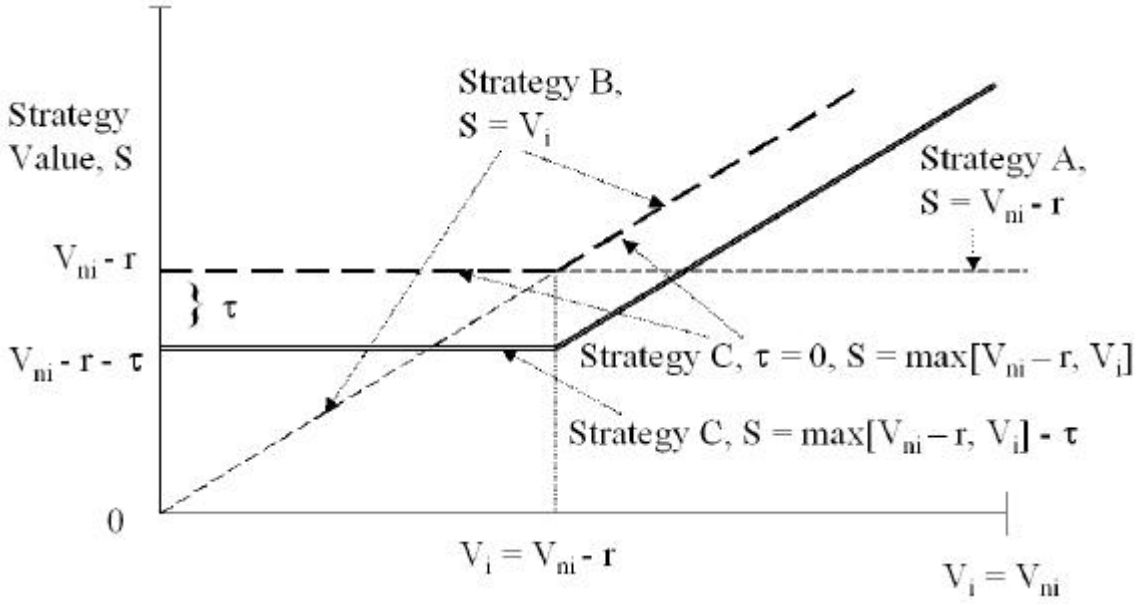

FIGURE 1. Comparison of *ex post* values of the three strategies

either of the other strategies because it combines the best outcomes of the other strategies but at no extra cost.

An interpretation of strategy C in Figure 1 that focuses on the maximization statement might view the option to spray as a long call commodity option on V_i with strike price $V_{ni} - r$: $U_c(\theta) = E\{\max[V_i - (V_{ni} - r), 0] \mid \theta\} + (V_{ni} - r) - \tau$. The strike price is the realization of V_i such that the grower is indifferent between spraying post-emergence and not spraying at that time.

We will now establish how the continuum of types may be partitioned according to strategies taken when $\tau > 0$. Notice that the type that is indifferent between strategies A and C, $\theta_{c,a}$, solves

$$\tau = r - E\{\min[r, V_{ni} - V_i] \mid \theta_{c,a}\}. \tag{3}$$

As with $\theta_{b,a}$, there may not be a unique solution. The solution set, $\Theta_{c,a}$, is convex, and we study $\hat{\theta}_{c,a} = \sup\{\theta_{c,a} : \theta_{c,a} \in \Theta_{c,a}\}$ so that ties are assigned to Strategy C. Calculus

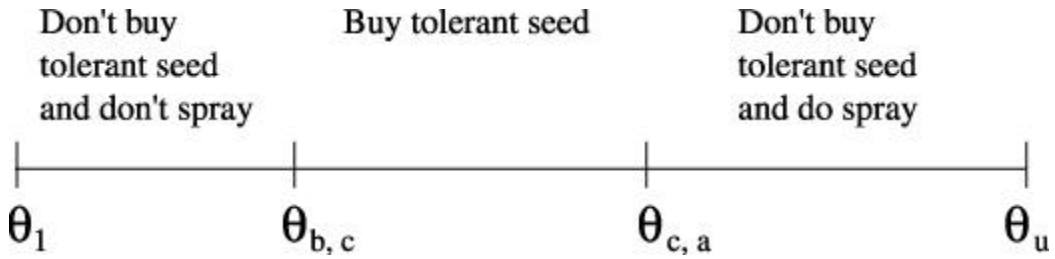

FIGURE 2. Partition of types by seed and spraying strategies adopted

then establishes $d\hat{\theta}_{c,a}/d\tau = -1/E_{\theta}\{\min[r, V_{ni} - V_i] \mid \theta\} < 0$. Notice also that the type(s) that is indifferent between time 0 strategies C and B, $\theta_{b,c} \in \Theta_{b,c}$, solves

$$\tau = E\{\max[V_{ni} - r - V_i, 0] \mid \theta_{b,c}\}. \tag{4}$$

With $\hat{\theta}_{b,c} = \sup\{\theta_{b,c} : \theta_{b,c} \in \Theta_{b,c}\}$, then $d\hat{\theta}_{b,c}/d\tau = 1/E_{\theta}\{\max[V_{ni} - r - V_i, 0] \mid \theta\} > 0$.

The partition of types adopting different strategies is as given in Figure 2, where, as we will show shortly, $\hat{\theta}_{b,c} \le \hat{\theta}_{b,a} \le \hat{\theta}_{c,a}$. Low θ types do not spray at all because the expected damage does not warrant the cost of a certain spray or the cost of an option to spray. Intermediate types are willing to buy the option to spray, at premium τ. High types may spray anyway because the price τ exceeds the value that these types place on flexibility. In light of Figure 2 we have that the τ-conditioned interval $(\hat{\theta}_{b,c}(\tau), \hat{\theta}_{c,a}(\tau)]$ is squeezed on both sides as τ increases.

Figure 3 depicts the impacts of an increase in τ on the partition of types according to strategies chosen. The function $U_c(\theta; \tau = 0)$ must be higher than both $U_b(\theta)$ and $U_c(\theta)$ because, as we have already demonstrated, $U_c(\theta; \tau = 0) \ge \max[U_b(\theta), U_a(\theta)]$. As τ increases, $U_c(\theta)$ shifts down so that the vertical difference between curves is the constant τ. Function $U_c(\theta)$ must cut function $U_b(\theta)$ from below because $dU_c(\theta)/d\theta \ge dU_b(\theta)/d\theta$, while function $U_c(\theta)$ must cut function $U_a(\theta)$ from above because $dU_c(\theta)/d\theta \le dU_a(\theta)/d\theta = 0$.[9] The "choke" price, above which no acre is

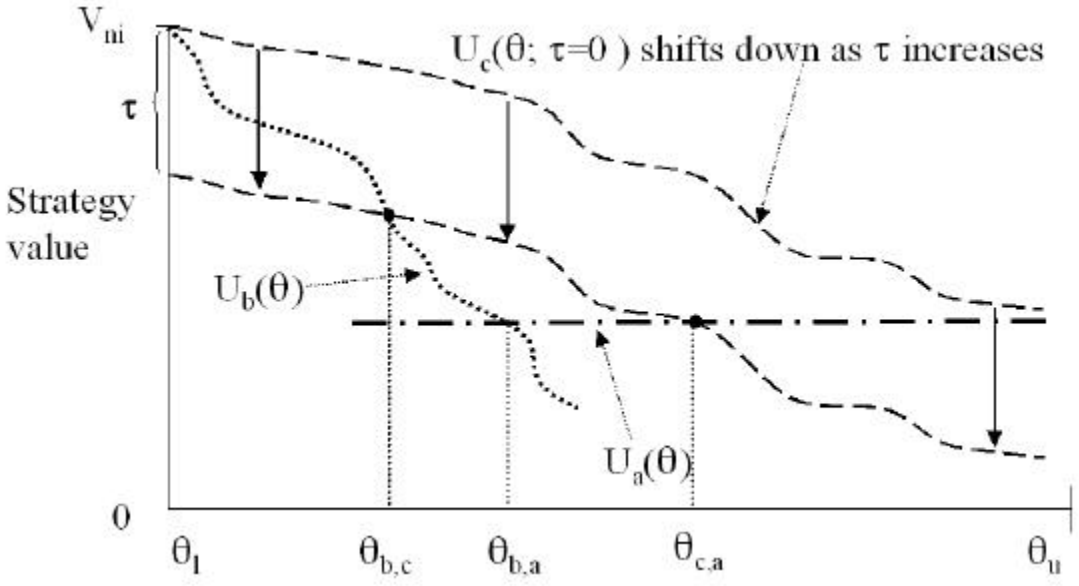

FIGURE 3. Effect of trait price on partition of types by strategies chosen

planted under a PT seed, is given by τ^+ where τ^+ is defined by $\theta^+ = \hat{\theta}_{c,a}(\tau^+) = \hat{\theta}_{b,c}(\tau^+)$. It is clear that, as in (1) above, $\theta^+ \equiv \hat{\theta}_{b,a}$.

Next we engage in a farm-level (i.e., partial equilibrium) analysis of the strategies chosen. Let γ parameterize a mean-preserving spread in $G(V_i \mid \theta)$ for all θ. From (3) and the concavity of the function $\min[r, V_{ni} - V_i]$ in V_i, it is clear that $d\theta_{c,a}(\tau)/d\gamma \geq 0$; an increase in the variability of an infestation, given that it occurs, increases the prospects of getting by without spraying. Purchasing the option to spray caps the loss at r. The opportunity to limit downside risk and yet benefit from upside potential will dispose the grower toward waiting rather than spraying for certain.

Applying (4), the convexity of the function $\max[V_{ni} - r - V_i, 0]$ in V_i assures us that $d\hat{\theta}_{b,c}/d\gamma \leq 0$. Owning the time 0 option to spray becomes more valuable, relative to either not owning or not spraying before emergence, when V_i becomes more random for any θ. This is because the option provided by the trait establishes a floor on the crop

value net of spraying costs, $V_{ni} - r$. The increase in risk provides more in the way of upside potential from spraying if an infestation warrants it but has limited effect on downside consequences. Therefore, acres switch from strategy B to strategy C at any given trait premium value, τ. We can see then that the (τ, γ)-conditioned interval, $(\hat{\theta}_{b,c}(\tau,\gamma), \hat{\theta}_{c,a}(\tau,\gamma)]$, of acres on which PT seed is planted expands on both sides as γ increases.

Summarizing our characterization of the types that buy the trait, we can write the following:[10]

RESULT 1. *For exogenous trait value,* $\tau \geq 0$,

a. $\hat{\theta}_{c,a} \geq \hat{\theta}_{b,c}$,

b. $I^c(\tau_2, \gamma) \subseteq I^c(\tau_1, \gamma)\ \forall \tau_2 \geq \tau_1, \forall \gamma$ *where* $I^c(\tau, \gamma) = (\hat{\theta}_{b,c}(\tau, \gamma), \hat{\theta}_{c,a}(\tau, \gamma)]$,

c. $I^c(\tau, \gamma_2) \supseteq I^c(\tau, \gamma_1)\ \forall \tau \geq 0, \forall \gamma_2 \geq \gamma_1$.

Part (*b*) points to an issue that does not appear to be generally recognized. Observe first that the innovation can be effectively "un-invented" by increasing price τ to an arbitrarily large value. Then, while a decline in τ would increase demand for the option to wait, part (*b*) does not assert where the weight of the increase in demand would come from. Viewing Figure 2, suppose that the distribution of types is massed largely toward the right. Then the innovation will reduce demand for the chemical. If, however, the distribution is massed largely toward the left, then demand for the chemical may rise on average after the innovation as growers find new uses for the (now) more versatile chemical.

Part (*c*) also warrants further reflection. It is the time point 1 revelation of complete information about the extent of the time point 1 pest problem that motivates an increase in demand for the trait as the amount of initial uncertainty increases. Our model is not general enough to rigorously support the assertion that it is the acquisition of information over the period between a pre-emergence pesticide application and any post-emergence application that strengthens demand for the trait. Nonetheless, this intuition seems well-founded, and the PT trait technology likely complements information technologies or

managerial capacities that enable the manager to acquire and process relevant information over the pre-emergence, post-emergence interval. However, if all relevant information were known pre-emergence, then the trait would have zero value because there would be no option value to waiting.

Equilibrium Value of Tolerance Trait

Now we turn to the decision environment of the firm that holds the patent on the genetic trait. The firm is assumed to license the trait to seed companies for a royalty per bag of seed sold, and the seed companies pass the fee directly on to seed consumers. Total royalties amount to

$$R(\tau;\gamma) = \tau H(\hat{\theta}_{c,a}) - \tau H(\hat{\theta}_{b,c}). \tag{5}$$

Given that trait production costs are sunk, the patent holder will choose a value of τ that sets marginal revenue equal to zero. Part (*c*) of Result 1 then readily yields the following.

RESULT 2. *Receipts from trait royalties increase with a mean-preserving spread in* $G(V_i \mid \theta)$ *on all* $\theta \in [\theta_l, \theta_u]$.

To ascertain this, suppose that $\tau = \tau_1$ is chosen to maximize the value of (5) for a given value $\gamma = \gamma_1$. Then the value of γ increases to $\gamma = \gamma_2$. From part (*c*) of Result 1 we have that demand, $H(\hat{\theta}_{c,a}) - H(\hat{\theta}_{b,c})$, increases for $\tau = \tau_1$. And the re-optimized value of $R(\tau; \gamma_2)$ can be no smaller than $R(\tau_1; \gamma_2)$. So there exists a $\tau = \tau_2$ such that $R(\tau_2; \gamma_2) \geq R(\tau_1; \gamma_2) \geq R(\tau_1; \gamma_1)$.[11]

Distribution of Types

The analysis underlying Figure 3 suggests that it is to the benefit of the trait monopolist for types to be intermediate in value rather than massed at the extremes of the types interval. Economic intuition might suggest that what is good for the trait mo-

nopolist would be bad for the aggregate welfare of growers. In this section we will provide precise conditions under which a reduction in heterogeneity among acres is to the benefit of the trait monopolist.

We already have noted from equations (3) and (4) that the values of indifferent types $\theta_{c,a}$ and $\theta_{b,c}$ are not directly dependent on the mass distribution $H(\theta)$. Fixing the value of τ, suppose now that mass is shifted from outside the interval $I^c(\tau) = (\hat{\theta}_{b,c}(\tau), \hat{\theta}_{c,a}(\tau)]$ to inside the interval. This certainly will be to the benefit of the trait patent holder because profit increases at any fixed trait price. However, and albeit indirectly, the sort of shift that we have just outlined is dependent upon the initial mass distribution $H(\theta)$ because $H(\theta)$ determines the monopolist's trait pricing decision. It has already been shown that $I^c(\tau) = (\hat{\theta}_{b,c}(\tau), \hat{\theta}_{c,a}(\tau)]$ contracts to the point $\hat{\theta}_{b,a}$ as $\tau \to \tau^+$. If $\tau < \tau^+$, then demand for the trait will always increase whenever the distribution of types undergoes a contraction about $\hat{\theta}_{b,a}$.

DEFINITION 1. *Mass distribution $H(\theta)$ is said to undergo a contraction about $\hat{\theta}_{a,b}$ if $H(\theta) \to \mathrm{H}^1(\theta)$ such that $\int_{\theta_l}^{\theta_u} dH(\theta) = \int_{\theta_l}^{\theta_u} dH^1(\theta)$ and $\int_B dH(\theta) \int_B dH^1(\theta)$ for all intervals $B \subseteq [\theta_l, \theta_u]$ such that $\hat{\theta}_{b,a} \in B$.*

This form of contraction need not be mean-preserving. It could be either mean-increasing or mean-decreasing. But if it does preserve the mean then the contraction is a mean-preserving contraction (mpc) in the sense of Rothschild and Stiglitz (1970). Further, not every mpc is an mpc about $\hat{\theta}_{b,a}$. In fact, a little work would demonstrate that even if $\hat{\theta}_{b,a} = \int_{\theta_l}^{\theta_u} \theta \, dH(\theta)$, then an mpc in the sense of Rothschild and Stiglitz would not necessarily satisfy the definition. An immediate consequence of the fact that a mass shift in types satisfying the definition increases trait demand for all trait prices is as follows:

RESULT 3. *If the distribution of acre types undergoes a contraction about $\theta_{b,a}$ then the trait patent holder's profits increase.*

The Pesticide Resistance Trait

This section outlines the impacts that the addition of the PR trait innovation would have on strategies and trait royalties. The strategy of sowing the PR trait at time 0 is labeled strategy D. As before, let there be three time points, 0, 1, and 2. At time point 0 the variety is purchased and planted. It may be a PT variety or a PR variety where the trait premium on the PR variety is ρ. The traits will not be stacked because the PT trait provides no value in addition to the PR variety. The PR premium must not exceed the cost of a pre-emergence spray, *r*, because otherwise strategy A would dominate the strategy of planting a PR variety, i.e., strategy D. If the resistance trait is purchased, then value is assuredly $V_{ni} - \rho$.

Equating expected payoffs under the resistant variety and the PT variety, the trait premium such that the risk-neutral grower managing a type θ acre is indifferent is given by

$$\rho = V_{ni} - E\{\max[V_{ni} - r, V_i] \mid \theta\} + \tau = \mathrm{E}\{\min[r, V_{ni} - V_i] \mid \theta\} + \tau. \qquad (6)$$

This establishes the determinants of the magnitude of the positive number $\rho - \tau$. Further, because $\min[r, V_{ni} - V_i]$ is concave in crop value, we can see that the private value added of the PR trait relative to the PT trait is *decreasing* in a mean-preserving spread of the random variable. Even without the PR trait, the grower has an insured floor in that a time-point 1 spray is possible. With only the PT trait we already have observed that the grower's position may be viewed as a long call option on the commodity. Then, the time 0 value of the position increases as the riskiness of any infestation increases. With the more valuable PR trait instead, this risk becomes irrelevant because the insured floor is replaced by complete insurance.

In an environment where growers are less than perfectly informed, growers of a PT variety likely will not execute their time-1 option well. Therefore, the likely impact of less information is to reduce the value of $E\{\max[V_{ni} - r, V_i] \mid \theta\}$. From (6) we then see that, upon fixing the acre type, the likely impact on ρ is for it to increase under less information. Thus, in a less well informed environment and when the pesticide tolerance trait price is fixed, more acres likely will be sown to the PR variety because poor-quality

information is not a problem under the latter technology. Consequently, the PR trait likely substitutes for a decision environment in which good post-emergence pest information is available.

Conclusion

In this paper we have placed state-contingent, cost-saving crop traits in a real options framework so as to better understand the implications of such traits for equilibrium production strategies when acres are heterogeneous. The analysis may warrant an extension to look more closely at welfare effects. Also, an elaboration to capture the effect of a novel trait on incentives to accumulate information about the decisions that may have to be made may be worth the effort. While undoubtedly challenging, such an extension would provide insights into the effects of trait innovations on temporal patterns in agri-input use. Policies to promote or deter the use of a trait because of alleged environmental effects may be formed after viewing the short-run effects on input use. But, given that growers in a relatively uninformed decision environment likely will avail themselves of new strategic opportunities, it is not immediately clear that the long-run effects on input use will be qualitatively the same as the shorter-run effects.

At the most general level, we conclude that while biotechnology trait innovations, agri-chemical use, and demand for farm-level information acquisition and processing inputs are intimately related, broad statements about the nature of interactions should be treated with some suspicion. Nonetheless, we end with some speculations that might warrant further inquiry.

While interactions between technology choices and input choices may generally reveal themselves over a relatively short time span, this is likely to be less true for some aspects of choices in information processing capacities. Education and the acquisition of skills are key issues here. To the extent that education strengthens managerial competencies in processing information, a biotechnology trait that demands, say, extensive decision making may find more adopters in a well-educated farm sector. And then, information and information management inputs will increase as factors in agricultural outputs. Further, the demand for education as an input in the sector will strengthen. But human capital formation can be a long-run phenomenon, and it may take some years for

enlightening empirical evidence to accumulate on how biotechnology interacts with the demand for education on the part of farm managers. Even in the more general set of agricultural technologies, Huffman (2001) has identified a dearth of research on how schooling, information acquisition, and technology adoption decisions interrelate.

Shifts in the structure of consumer preferences are likely to strengthen the need for such research. The growing market penetration of the organic food movement (Duram 1998), with its disposition toward technology choices that are conditioned on the production environment, will require of growers the capacity to acquire and use information in matching the environment with the suite of available production technologies. Also, the U.S. Food Quality Protection Act of 1996 may eventually result in the removal of a large number of pesticides from many of their agricultural uses. Food quality traits, including visual traits, likely are luxuries. Producers seeking to satisfy the demands of increasingly affluent consumers may have to recourse to a mixed bag of environment-specific technologies. The decision environment may become more complicated, and there may be premiums for managers who know their production environment well enough to judiciously exercise their technology options.

On the other hand, if PR and other genetic traits substitute for informed farm-level decision making, then the agricultural crop economy may become more centralized. The information disadvantages facing cropland renters would become relatively less severe, while scale economies in asset management and reduced unit input costs may dominate in determining firm structure.

Endnotes

1. The number excludes non-regulated technologies and thus likely significantly undercounts innovation in this area.

2. Bridges's numbers broadly concur with field trial data presented in National Research Council 2000, page 170.

3. By July 2002, rootworm resistant corn seed by Monsanto had received most of the clearances necessary for commercial use in the United States.

4. MacRae (2002) writes, "The basis of Precision Agriculture is applying agrochemicals only where necessary. The point of Integrated Pest Management is to apply pesticide only when it is necessary. By using these technologies in IPM, we can develop 'Precision IPM,' only applying pesticides where and when it is necessary."

5. Other recent work in agricultural production economics has applied the continuous time stochastic diffusion tools that are, perhaps, most readily associated with real options theory. These include Saphores's (2000) work on intra-season control of fruit crop pests through a sequence of sprays. The real option we identify fits naturally into a two-period model, and we have no need to adopt the parametric constraints that attend the continuous time framework.

6. Note in particular that we have assumed that no reinfestation occurs if strategy A is chosen.

7. We have $U_c(\theta) - U_b(\theta) = E\{\max[V_{ni} - r - V_i, 0] \mid \theta\} - \tau$ with non-negative derivative. And we have $U_a(\theta) - U_c(\theta) = E\{\min[r, V_{ni} - V_i] \mid \theta\} + \tau - r$, again with non-negative derivative.

8. This can also be seen as an application of Jensen's inequality since the function $\max[V_{ni} - r, V_i]$ is convex in V_i.

9. See the calculations in endnote 7.

10. It is only due to the convention that distribution functions are right continuous that $I^c(\tau, \gamma)$ is open on the left.

11. The comparative statics of τ are somewhat more involved. Assumptions are then required on the distribution of types in order to guarantee an unique equilibrium. Some results are available from the authors upon request.

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